



Advanced Gasoline Turbocharged Direct Injection (GTDI) Engine Development

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Ford Research and Advanced Engineering

06/11/2015

Project ID: ACE065



◆ Timeline

- ◆ Project Start 10/01/2010
- ◆ Project End 12/31/2014
- ◆ No Cost Extension 09/30/2015
- ◆ Completed 85%

◆ Total Project Funding

- ◆ DOE Share \$15,000,000.
- ◆ Ford Share \$15,000,000.
- ◆ Funding in FY2014 \$ 2,428,972.
- ◆ Funding in FY2015 \$ NCE

◆ Barriers

- ◆ Gasoline Engine Thermal Efficiency
- ◆ Gasoline Engine Emissions
- ◆ Gasoline Engine Systems Integration

◆ Partners

- ◆ Lead Ford Motor Company
- ◆ Support Michigan Technological University (MTU)

- ◆ Ford Motor Company has invested significantly in Gasoline Turbocharged Direct Injection (GTDI) engine technology in the near term as a cost effective, high volume, fuel economy solution, marketed globally as EcoBoost technology.



- ◆ Ford envisions further fuel economy improvements in the mid & long term by further advancing the EcoBoost technology.
 - ◆ Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
 - ◆ Advanced lean combustion w/ direct fuel injection & advanced ignition
 - ◆ Advanced boosting systems w/ active & compounding components
 - ◆ Advanced cooling & aftertreatment systems

- ◆ Ford Motor Company Objectives:

- ◆ Demonstrate 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics.
- ◆ Demonstrate vehicle is capable of meeting Tier 3 SULEV30 emissions on FTP-75 cycle.



- ◆ MTU Objectives:

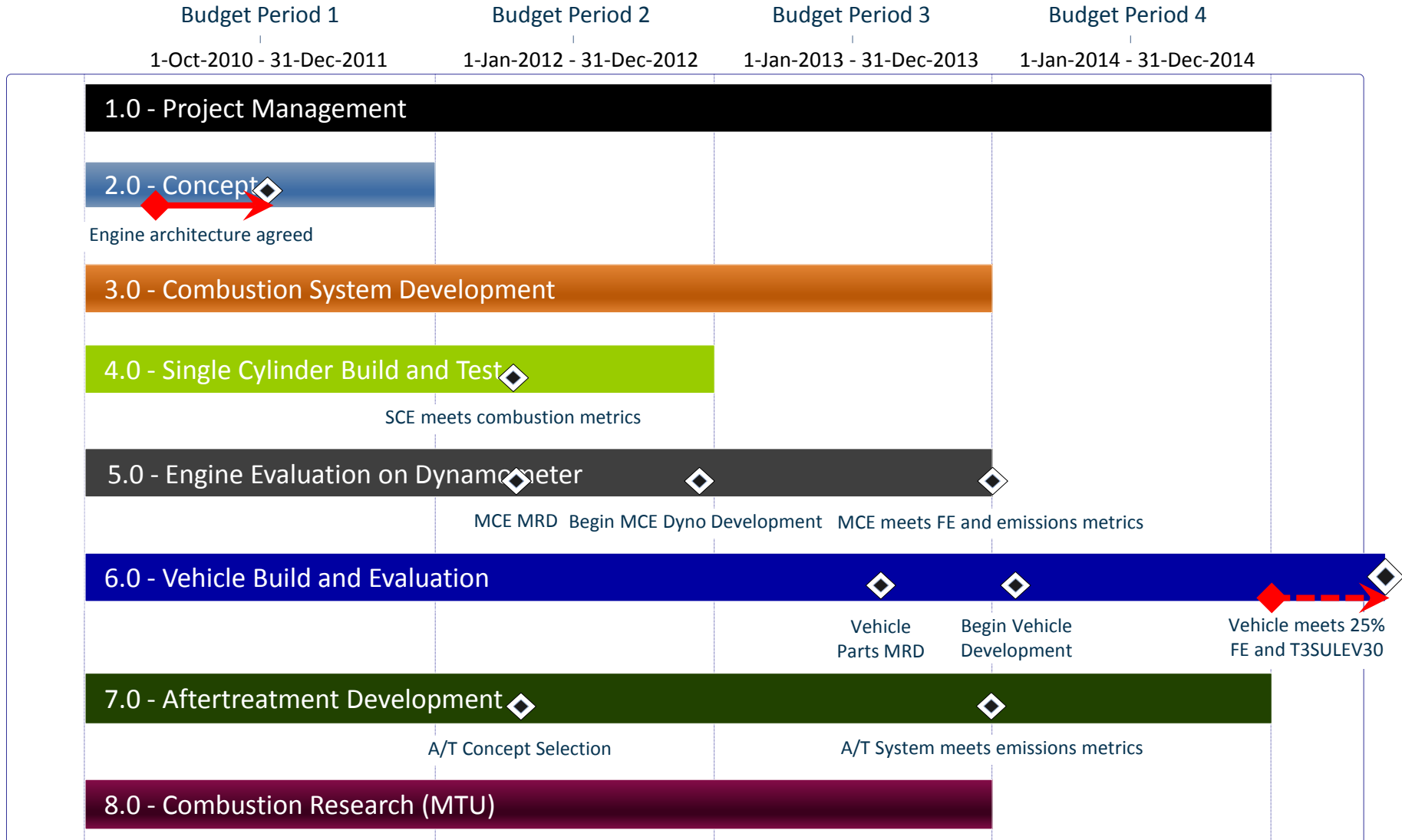
- ◆ Support Ford Motor Company in the research and development of advanced ignition concepts and systems to expand the dilute / lean engine operating limits.

- ◆ Engineer a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, including:
 - ◆ Aggressive engine downsizing in a mid-sized sedan from a large V6 to a small I4
 - ◆ Mid & long term EcoBoost technologies
 - ◆ Advanced dilute combustion w/ cooled exhaust gas recycling & advanced ignition
 - ◆ Advanced lean combustion w/ direct fuel injection & advanced ignition
 - ◆ Advanced boosting systems w/ active & compounding components
 - ◆ Advanced cooling & aftertreatment systems
 - ◆ Additional technologies
 - ◆ Advanced friction reduction technologies
 - ◆ Advanced engine control strategies
 - ◆ Advanced NVH countermeasures
- ◆ Progressively demonstrate the project objectives via concept analysis / modeling, single-cylinder engine, multi-cylinder engine, and vehicle-level demonstration on chassis rolls.

Milestone Timing

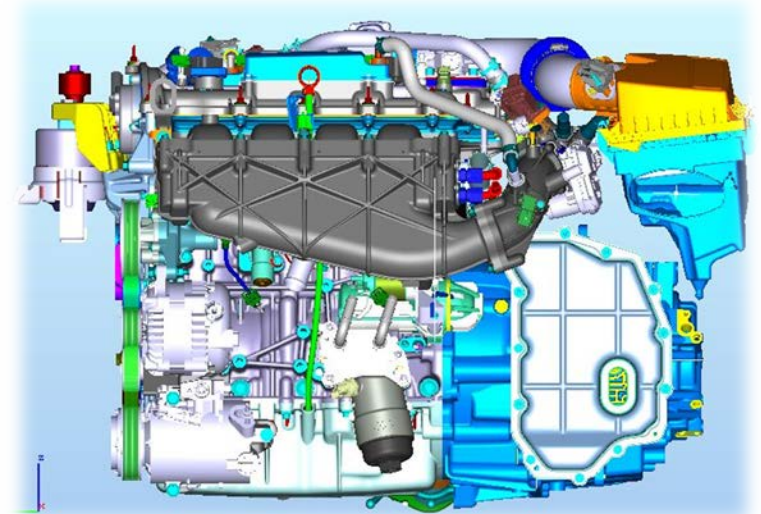


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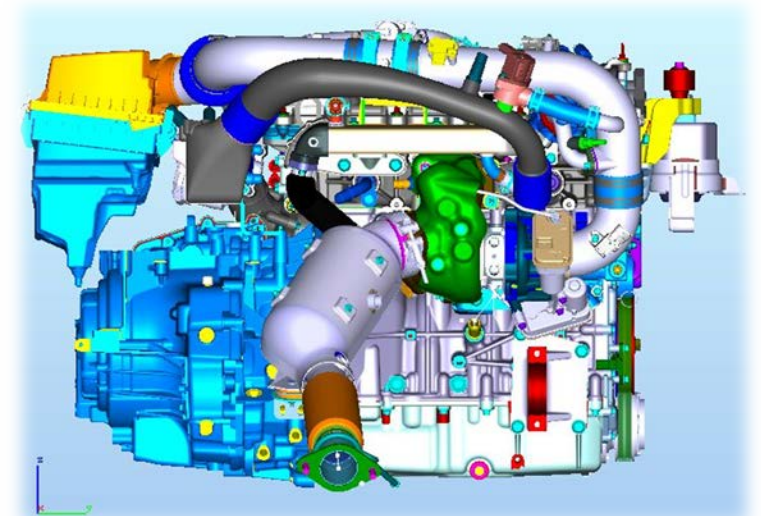
◆ Attribute Assumptions

Peak Power =	80 kW / L @ 6000 rpm
Peak Torque =	20 bar BMEP @ 2000 - 4500 rpm
Naturally Asp Torque @ 1500 rpm =	8 bar BMEP
Peak Boosted Torque @ 1500 rpm =	16 bar BMEP
Time-To-Torque @ 1500 rpm =	1.5 s
As Shipped Inertia =	0.0005 kg-m ² / kW



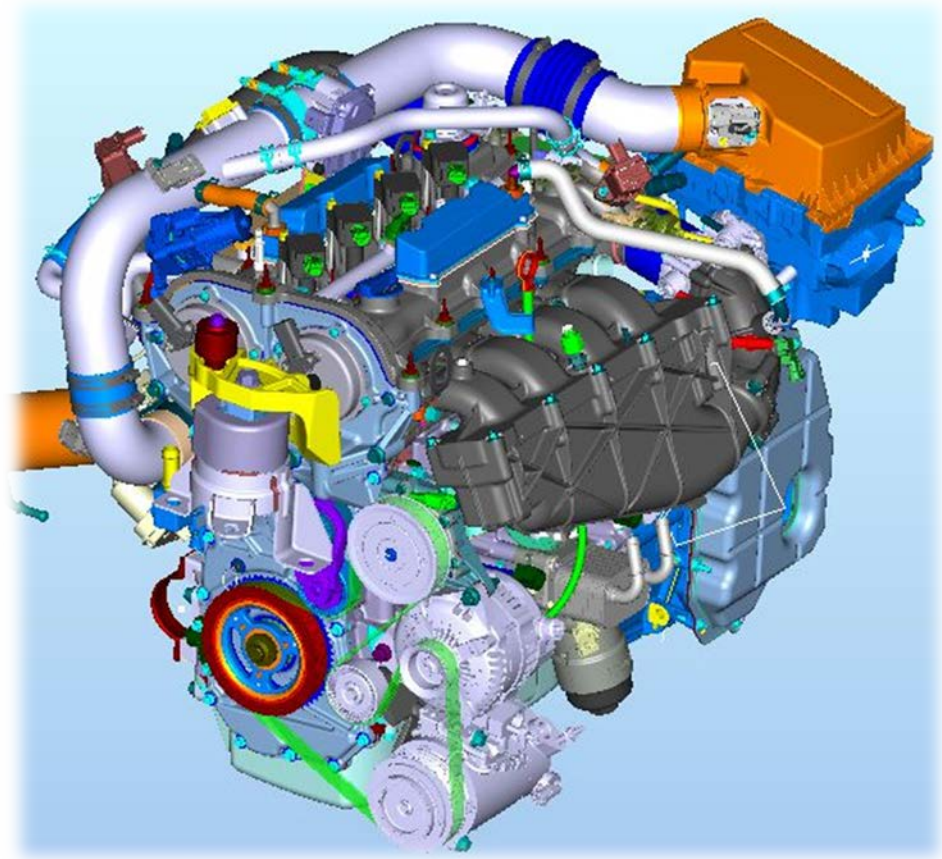
◆ Architecture Assumptions

Displacement / Cylinder =	565 cm ³
Bore & Stroke =	87.5 & 94.0 mm
Compression Ratio =	11.5:1
Bore Spacing =	96.0 mm
Bore Bridge =	8.5 mm
Deck Height =	222 mm
Max Cylinder Pressure (mean + 3 σ) =	100 bar
Max Exhaust Gas Temperature =	960 °C
Fuel Octane =	98 RON



◆ Systems Assumptions

- ◆ Transverse central DI + ignition w/ intake biased multi-hole injector
- ◆ Twin scroll turbocharger w/ scroll control valve + active wastegate
- ◆ Low pressure, cooled EGR system
- ◆ Composite intake manifold w/ integrated air-water charge air cooler assembly
- ◆ Split, parallel, cross-flow cooling with integrated exhaust manifold
- ◆ Integrated variable displacement oil pump / balance shaft module
- ◆ Compact RFF valvetrain w/ 12 mm HLA
- ◆ Roller bearing cam journals on front, all other locations conventional
- ◆ Electric tiVCT
- ◆ Torque converter pendulum damper
- ◆ Active powertrain mounts
- ◆ Assisted direct start, ADS
- ◆ Electric power assisted steering, EPAS
- ◆ Three way catalyst, TWC
- ◆ Lean NOx aftertreatment, LNT + SCR



- ◆ Detailed, cycle-based CAE analysis of fuel economy contribution of critical technologies

Architecture / System Assumption	% Fuel Economy	
3.5L V6 \Rightarrow 2.3L I4 High Expansion Ratio Architecture	+	15.6% - Engine Architecture / Downsizing
583 \Rightarrow 565 cm ³ Displacement / Cylinder	~	
1.07 \Rightarrow 0.93 Bore / Stroke	~	
10.3:1 \Rightarrow 11.5:1 Compression Ratio	+	
PFI \Rightarrow Transverse Central DI	-	
iVCT \Rightarrow Electric tiVCT	+	7.8% - Engine & As-Installed Systems
Split, Parallel, Cross-Flow Cooling & Integrated Exhaust Manifold	+	
Variable Displacement Oil Pump & Roller Bearing Cam Journals	+	
DAMB \Rightarrow Compact RFF Valvetrain	+	
3.5L V6 \Rightarrow 2.3L I4 Idle & Lugging Limits	-	
Torque Converter Pendulum Damper & Active Powertrain Mounts	+	
Assisted Direct Start, ADS	+	
Electric Power Assisted Steering, EPAS	+	4.4% - Air Path / Combustion
Active Wastegate	+	
Low Pressure, Cooled EGR System	+	
Lean NOx Aftertreatment, LNT + SCR	+	
Torque Converter & Final Drive Ratio	+	0.2% - Engine Match
Total	28.0	



2.3L MiGTDI Pre-XO Engine #1

- Displacement / Cylinder = 565 cm³
- Bore & Stroke = 87.5 & 94.0 mm
- Compression Ratio = 11.5:1
- Bore Spacing = 96.0 mm
- Bore Bridge = 8.5 mm
- Deck Height = 222 mm
- Transverse central DI + ignition w/ intake biased multi-hole injector
- Advanced boosting system + active wastegate
- Low pressure, cooled EGR system
- Composite intake manifold w/ integrated air-water charge air cooler assembly
- Split, parallel, cross-flow cooling with integrated exhaust manifold
- Integrated variable displacement oil pump / balance shaft module
- Compact RFF valvetrain w/ 12 mm HLA
- Roller bearing cam journals on front, all other locations conventional
- Electric tiVCT

Accomplishments



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#1 – Combustion System / Mechanical Verification



#2 – Cold Start Emissions Development



#3 – Steady State Mapping



#4 – Mechanical Friction Study \Rightarrow NVH Study

Phase 1 Build



#5 – Performance Development



#6 – Thermal Management Studies



#7 – Mechanical Development Studies



#8 – Spare 😊

Phase 2 Build

Phase 3 Build



#9



#11



#10



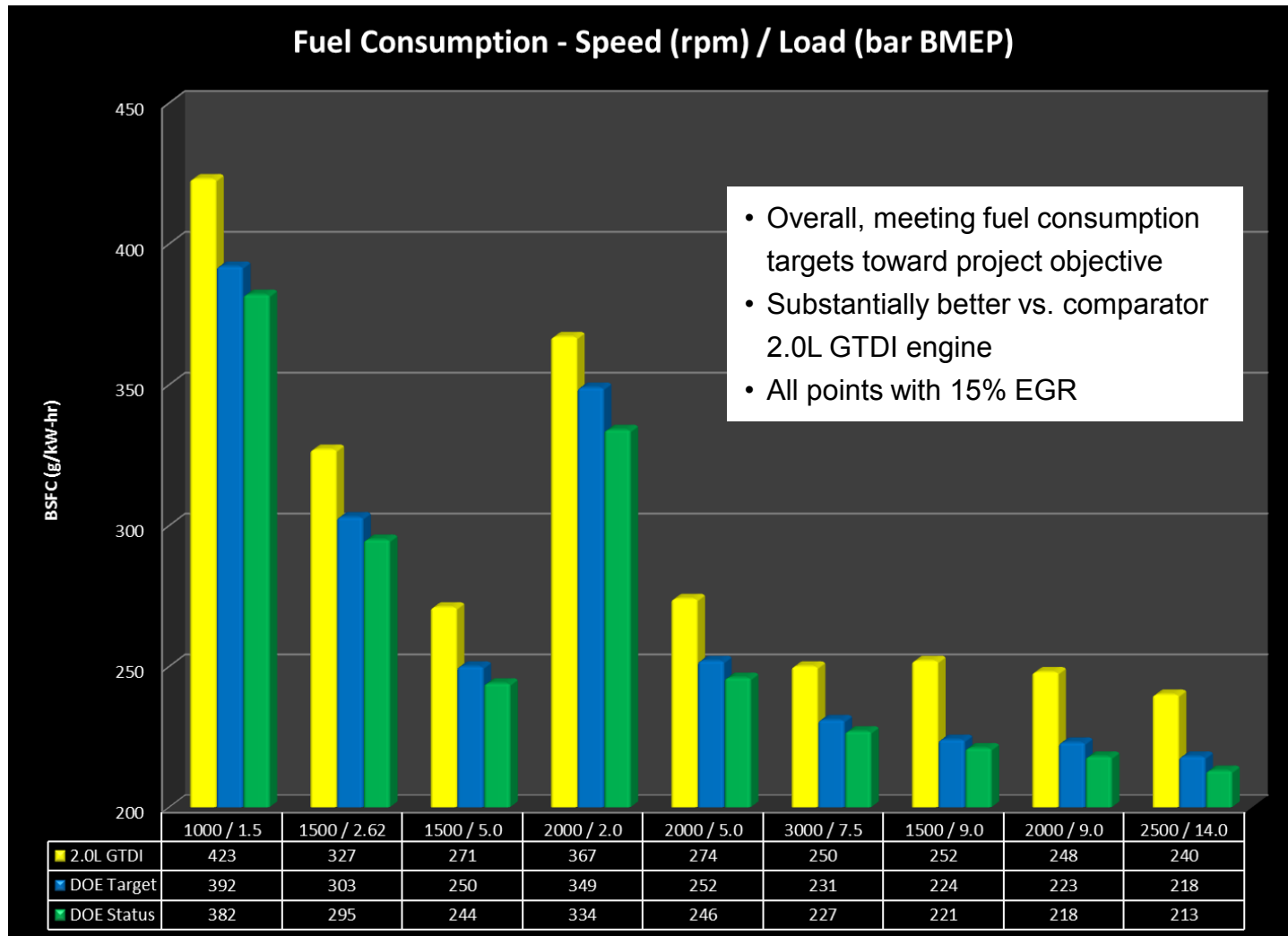
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Calibration

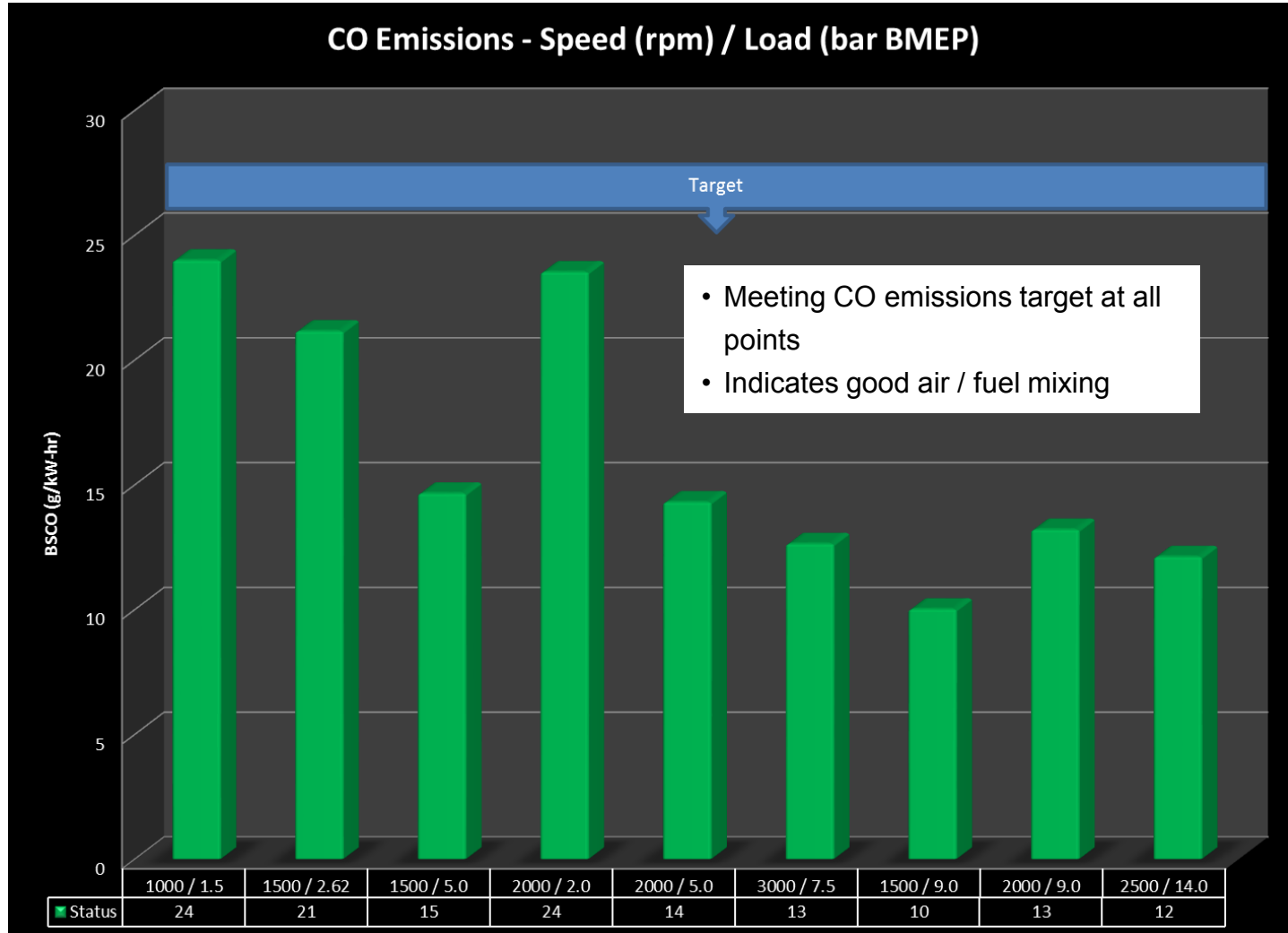
Vehicles (4)



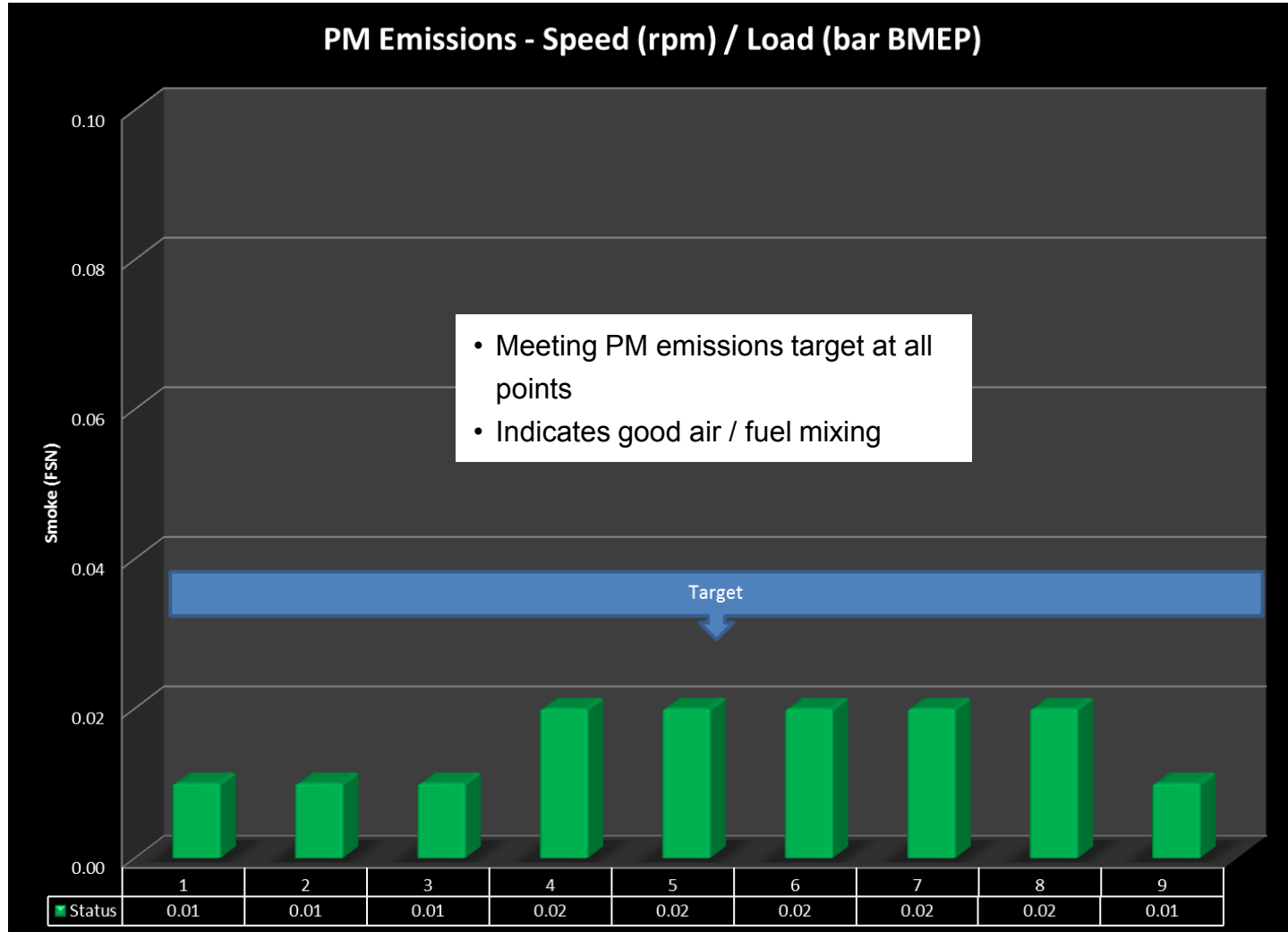
◆ MCE Evaluation on Dynamometer – Part Load Fuel Consumption



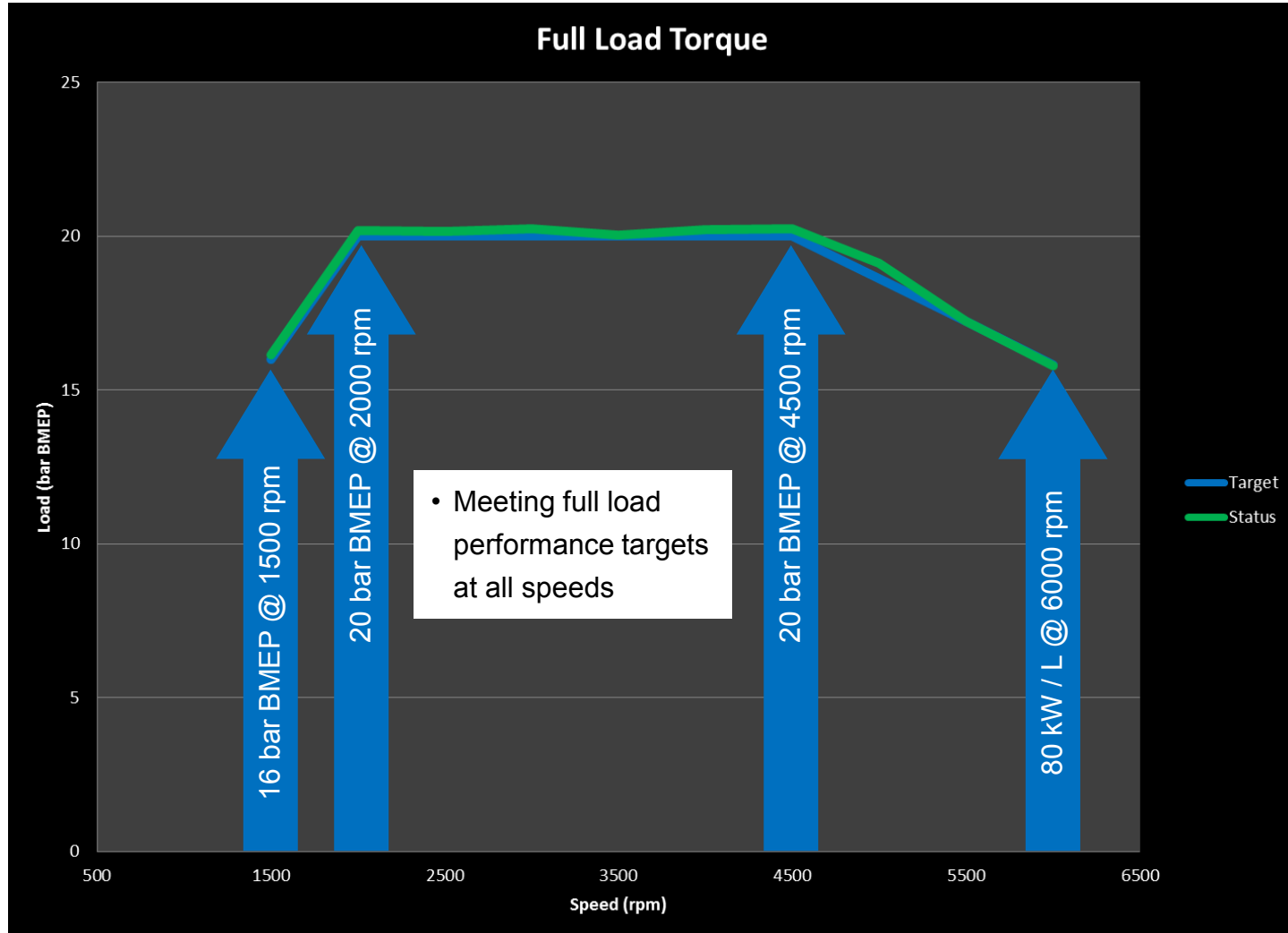
◆ MCE Evaluation on Dynamometer – Part Load CO Emissions



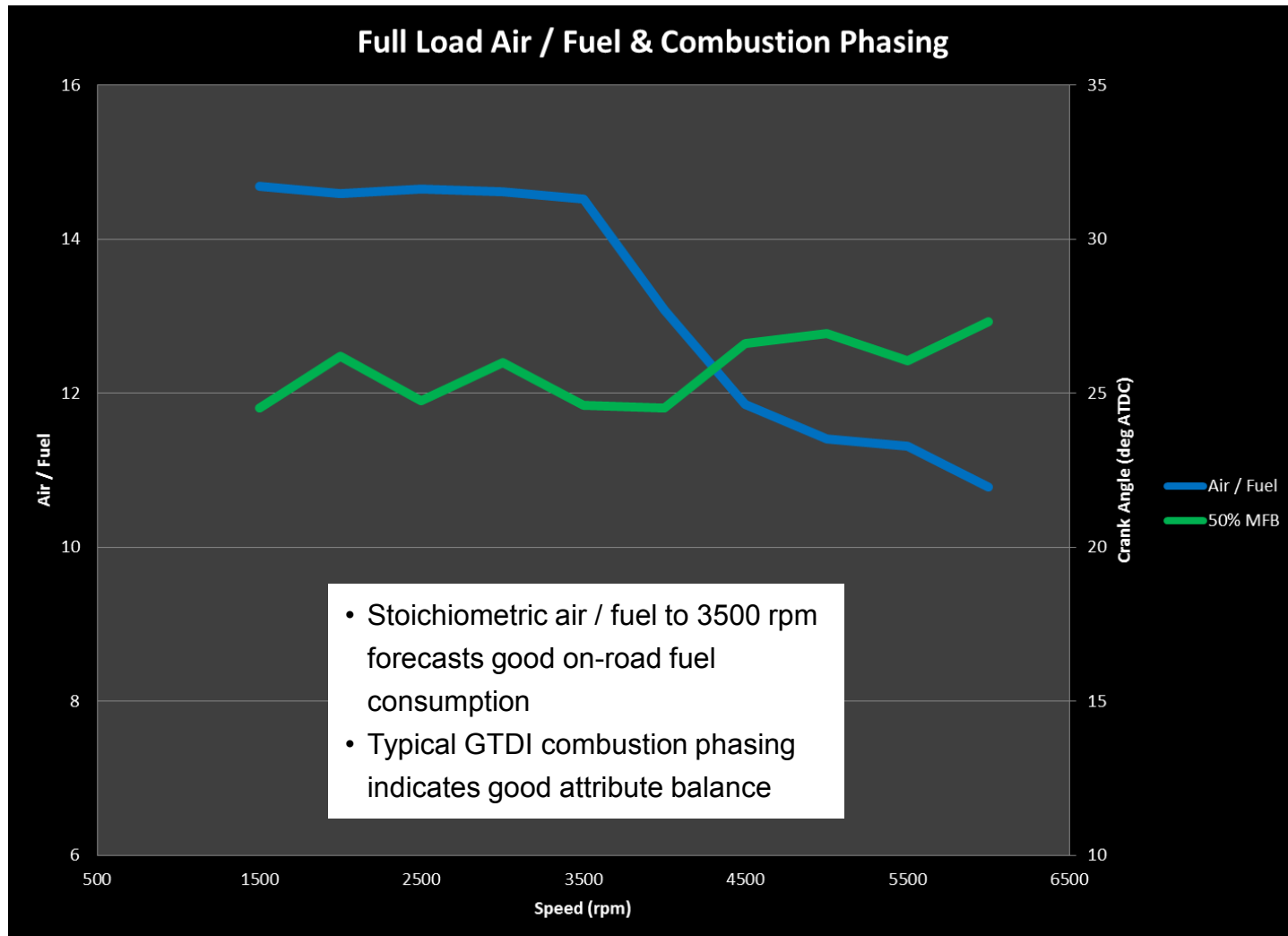
◆ MCE Evaluation on Dynamometer – Part Load PM Emissions



◆ MCE Evaluation on Dynamometer – Full Load Performance



◆ MCE Evaluation on Dynamometer – Full Load Performance



◆ MCE Evaluation on Dynamometer – Cold Start Emissions

- ✓ Completed transient emissions verification testing, including steady state cold fluids development and transient cold start development
- ✓ Received concurrence on transitioning Tier 2 Bin 2 to Tier 3 SULEV30 emissions

Tailpipe Standards	Tier 2 Bin 2	Tier 3 SULEV30
NMOG	10 mg / mi	--
NOx	20 mg / mi	--
NMOG + NOx	--	30 mg / mi
PM	10 mg / mi	3 mg / mi

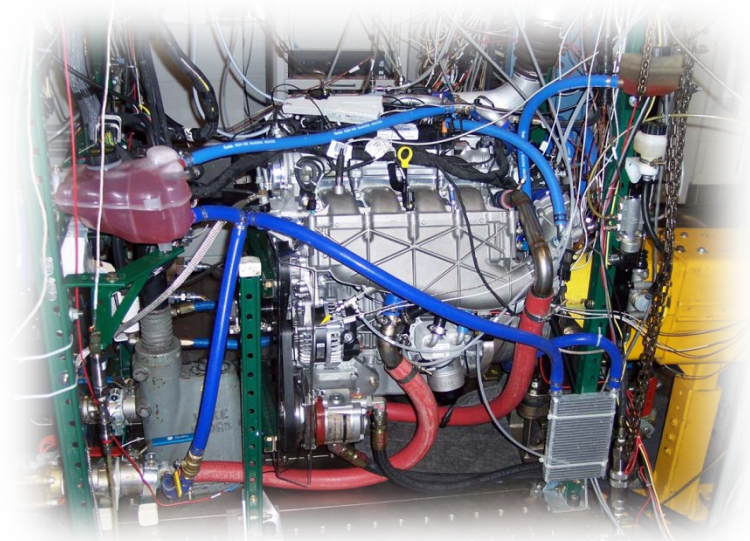
- ✓ Meeting 20°C Cold Start Feedgas Targets – Derived From Tailpipe Standards

Cold Start Attribute	Units	Target ¹	Status
0-20s Cumulative FGHC + FGNOx	mg	< 227	224
0-20s Cumulative Particulate Mass (PM)	mg	< 3.0	1.3
5-15s CSER stability (RMS_SDIMEP)	bar	< 0.350	0.375

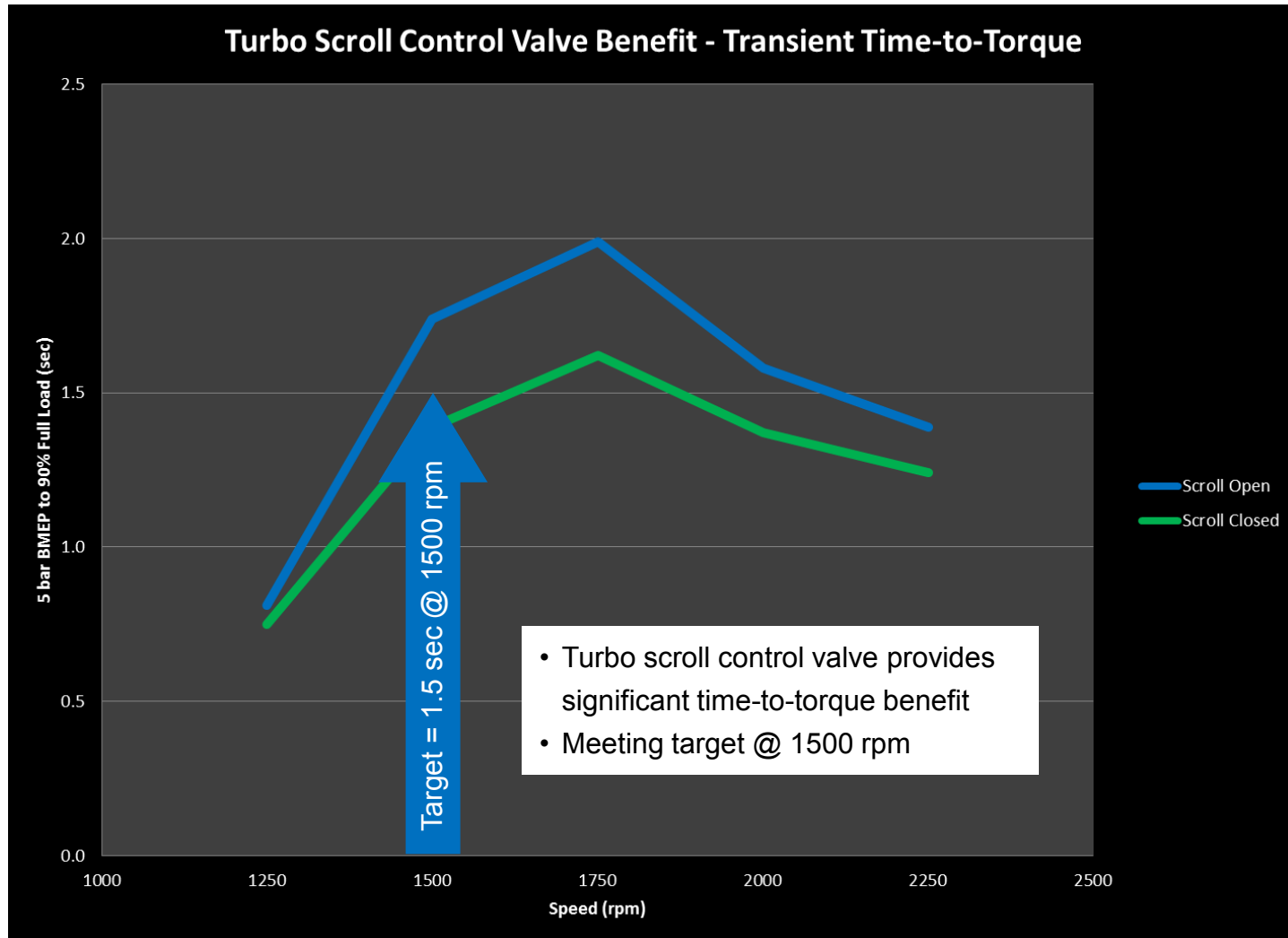
¹ Evaluated at a CSER heat flux that achieves ~350°C catalyst mid-bed @ 20 seconds after engine start

◆ MCE Evaluation on Dynamometer - Mapping

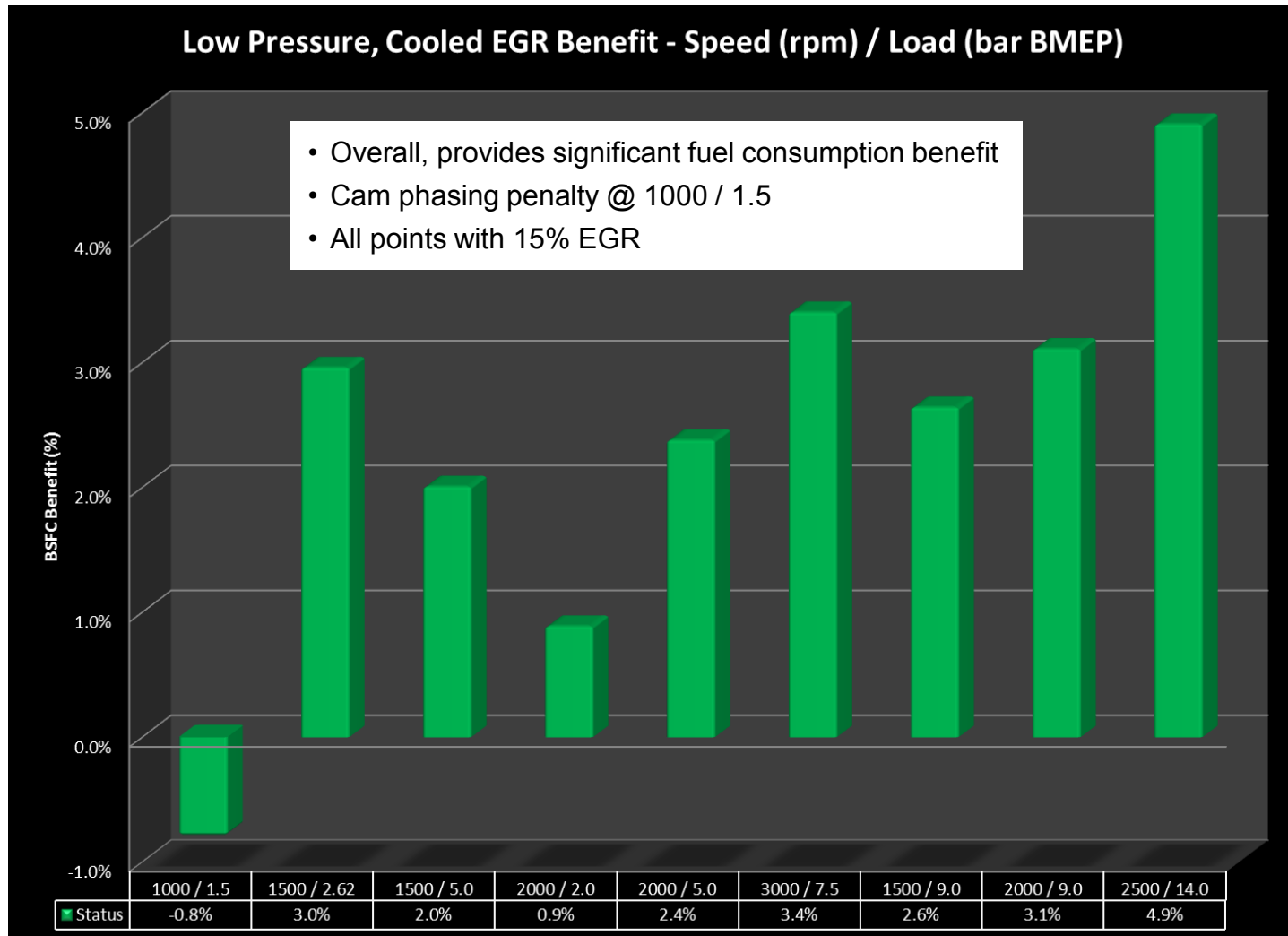
- ✓ Continued engine mapping in support of vehicle calibration, including effectively utilizing “auto test” control for autonomous engine mapping
 - ✓ Electric tiVCT Cam Timing Optimization
 - ✓ DI Fuel Injection Timing Optimization
 - ✓ DI Fuel Rail Pressure Optimization
 - ✓ Naturally-Aspirated Air Charge – Throttle Sweeps
 - ✓ Boosted Air Charge – Scroll / Wastegate Control Sweeps
 - ✓ Full Load Performance – BLD / MBT Spark Sweeps
 - ✓ Low Pressure Cooled EGR
- ✓ Continued mapping validation testing and additional detailed mapping factorials as required to ensure accuracy



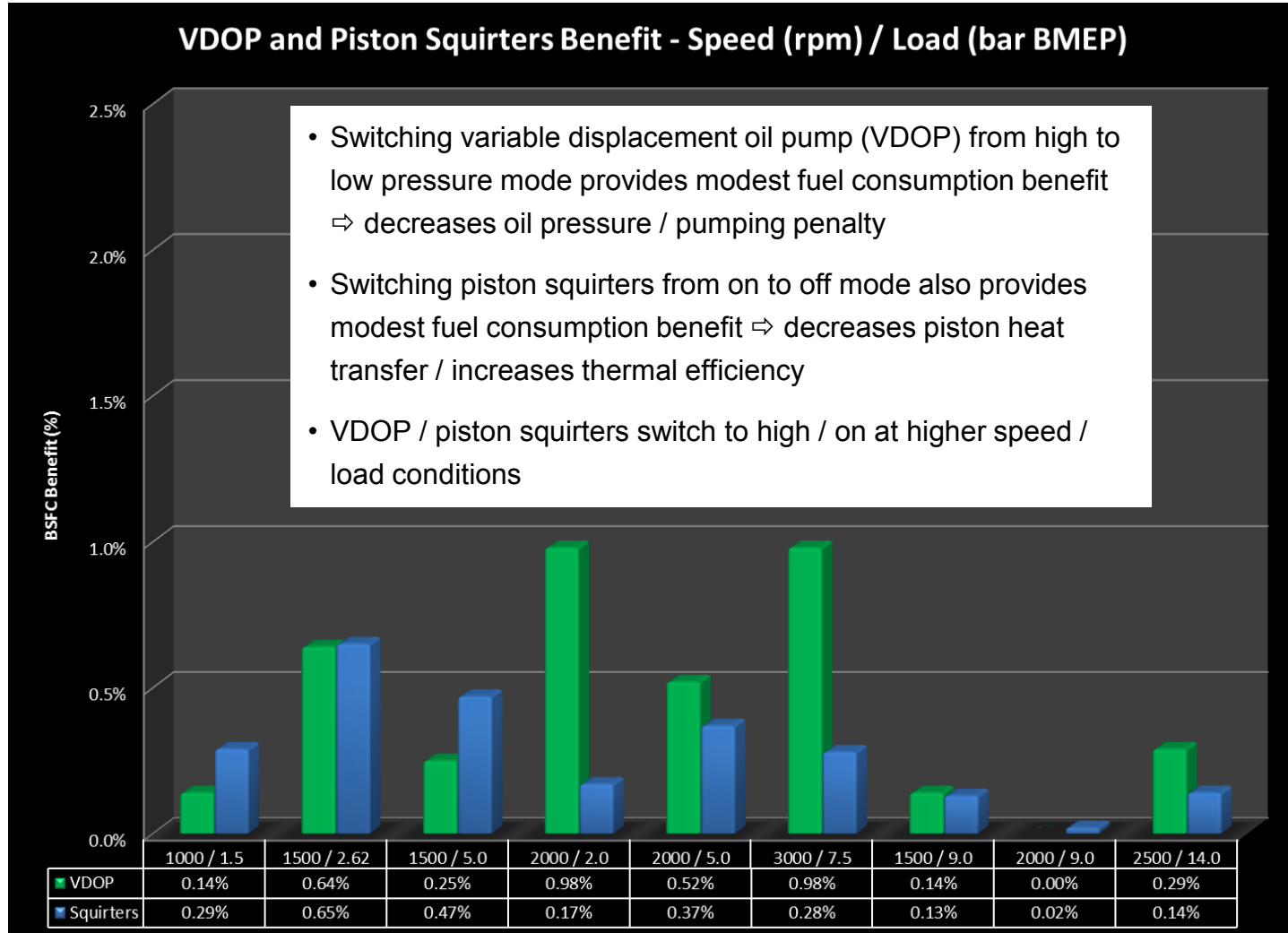
◆ MCE Evaluation on Dynamometer – Transient Time-to-Torque



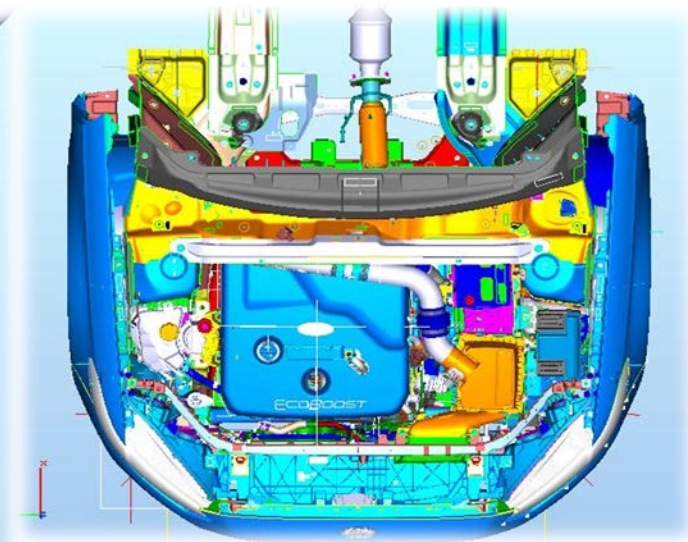
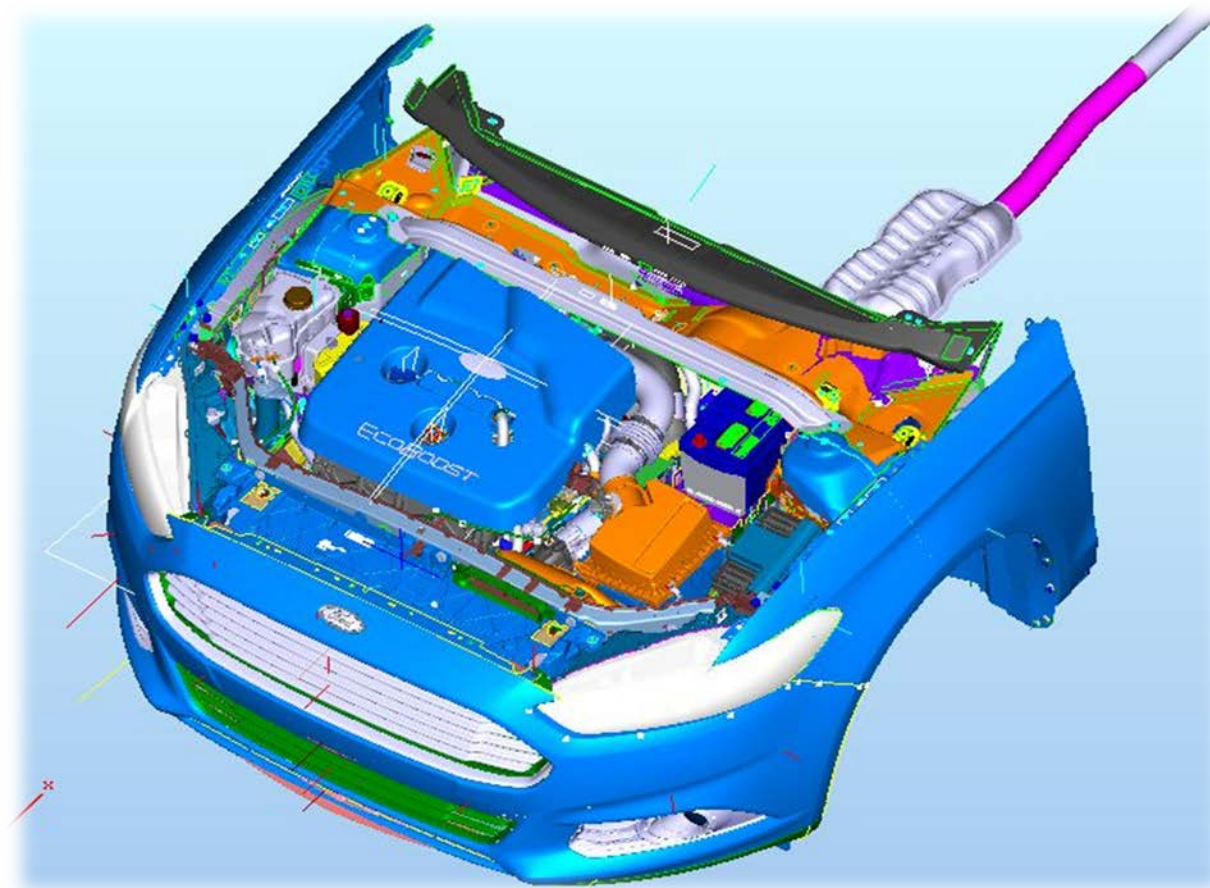
◆ MCE Evaluation on Dynamometer – Low Pressure, Cooled EGR



◆ MCE Evaluation on Dynamometer – VDOP and Piston Squirters



- ◆ Vehicle Build – Engine As Installed



- ◆ Vehicle Build – Engine As Installed



◆ Vehicle Development – Significant Progress toward Vehicle Demonstration

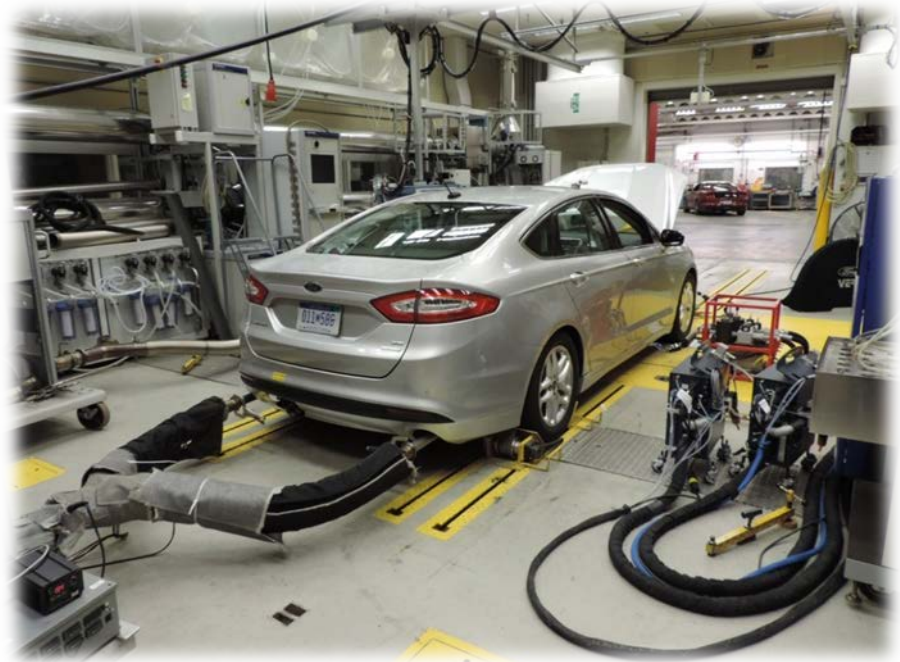
	Safe Calibration “Functional Verification”	Development Calibration “Full Transient Control”	Mature Calibration “Final Refinement”
Air Charge	✓	✓	✓
DI Fuel	✓	✓	✓
Spark	✓	✓	✓
Torque	✓	✓	✓
Boost – Scroll / Wastegate	✓	✓	✓
Cold Start / Warm Up	✓	✓	✓
Stop / Start	✓	✓	✓
Electric tiVCT	✓	✓	In Process
Cooling & Lubrication	✓	✓	In Process
Torque Converter Schedule	✓	✓	In Process
Shift Schedule	✓	✓	In Process
Low Pressure Cooled EGR	✓	In Process	Planned

- ◆ Vehicle Development – Calibration on Chassis Rolls in Process

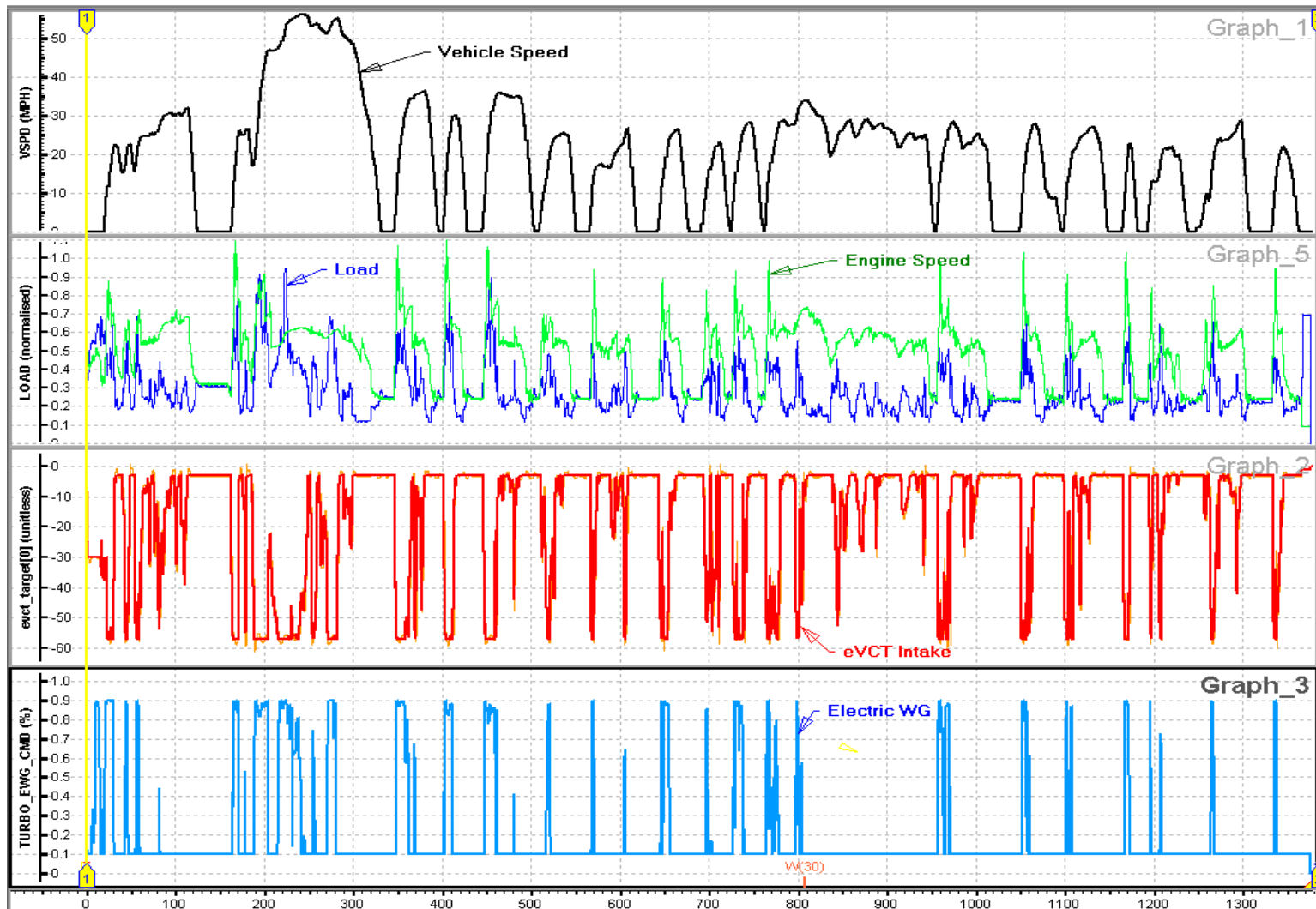


Complete fuel economy and emissions measurement capabilities enable rapid calibration refinement

Four (4) identical calibration vehicles enable continuous on-road development and productive chassis roll testing



- Vehicle Development – Initial FTP-75 Testing In Process (Bags 1 & 2 Shown)





- ◆ Vehicle Development – Plans to Final FTP-75 Testing
 - ◆ Electric tiVCT control & calibration for drivability & fuel economy
 - ◆ Torque converter schedule optimization for fuel economy
 - ◆ Shift schedule for drivability & fuel economy
 - ◆ Low pressure cooled EGR control & calibration for drivability & fuel economy

- ◆ Project meets all engine level targets for fuel consumption, emissions, and performance. Based on engine level and vehicle accomplishments to date, project is anticipated to meet vehicle level fuel economy and emissions objectives by 09/30/15.

- ◆ “The project is relevant to understand the opportunity for increased fuel economy at project emission targets.”
- ◆ “Lean combustion and aftertreatment studied, but are not part of final approach.”
 - ◆ Given the DeSOx challenges of a TWC + LNT / SCR system, and the uncertainty of a TWC + passive SCR system, received concurrence on lean aftertreatment transitioning to stoichiometric at the vehicle level.
 - ◆ Continued lean combustion “Micro” Stratified Charge development at the dyno level (results presented previously); lean aftertreatment challenges persist.
- ◆ “Encouraging dyno fuel economy results. No vehicle results shown.”
 - ◆ No cost extension to 09/30/15; vehicle chassis roll testing in process.



- ◆ Budget Period 4 – Vehicle Development 01/01/2014 – 09/30/2015
 - ◆ Vehicle demonstrates greater than 25% weighted city / highway fuel economy improvement and Tier 3 SULEV30 emissions on FTP-75 test cycle

- ◆ The project will demonstrate a 25% fuel economy improvement in a mid-sized sedan using a downsized, advanced gasoline turbocharged direct injection (GTDI) engine with no or limited degradation in vehicle level metrics, while meeting Tier 3 SULEV30 emissions on FTP-75 cycle.
- ◆ Ford Motor Company has engineered a comprehensive suite of gasoline engine systems technologies to achieve the project objectives, assembled a cross-functional team of subject matter experts, and progressed the project through the concept analysis, design, development, and evaluation tasks with material accomplishments through the duration of the project.
- ◆ The outlook for 2015 is stable, with accomplishments anticipated to track the original scope of work and planned tasks, with the exception of milestone "Vehicle demonstrates greater than 25% weighted city / highway fuel economy improvement and Tier 3 SULEV30 emissions on FTP-75 test cycle" deferred from 12/31/2014 to 09/30/2015.